High Power Density Motor Equipped with Additively Manufactured Windings Integrated with Advanced Cooling and Modular Integrated Power Electronics

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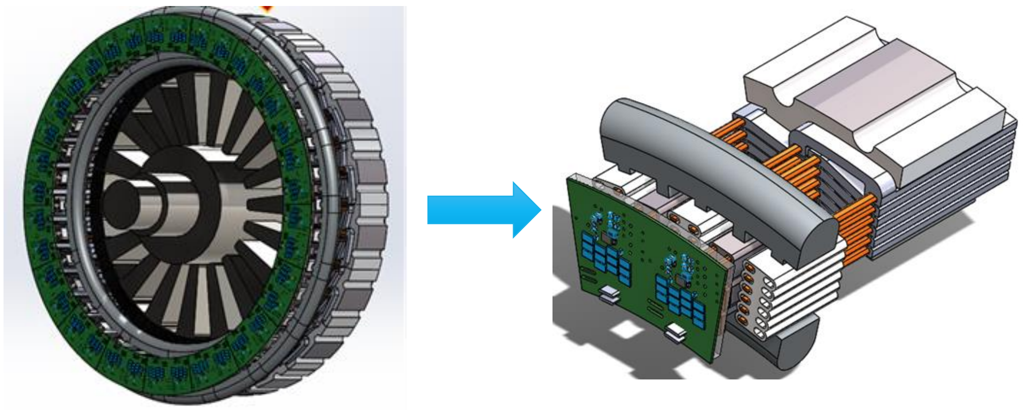
Project Vision

Unique additively-manufactured coils will enable direct cooling of the stator windings which bypasses the thick insulation needed. In addition, tight integration between the electric motor, power electronics and TMS will be enabled



REEACH / ASCEND / CABLES
Annual Program Review Meeting
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Brief ASCEND Project Overview

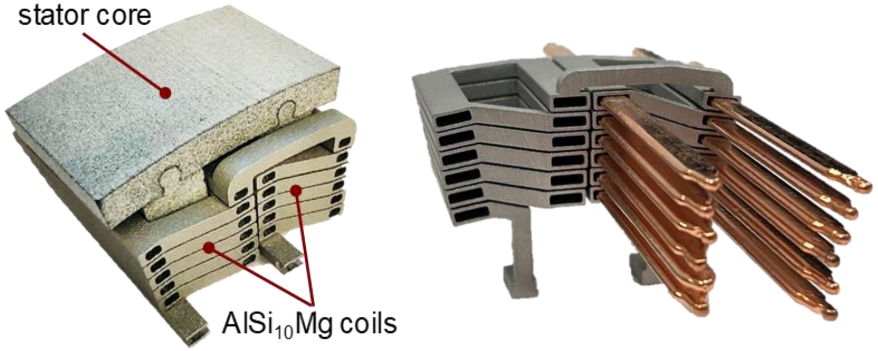
Team member	Location	Role in project
Marquette University	Milwaukee, WI	Motor and power converter development
Florida State University	Tallahassee, FL	Insulation system development
National Renewable Energy Lab	Golden, CO	TMS development
Raytheon Technologies Research Center	Hartford, CT	System integration and verification testing
Ampaire	Hawthorne, CA	Advisory role and T2M

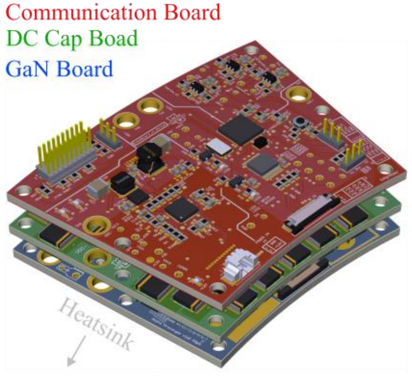
Context/history of the project

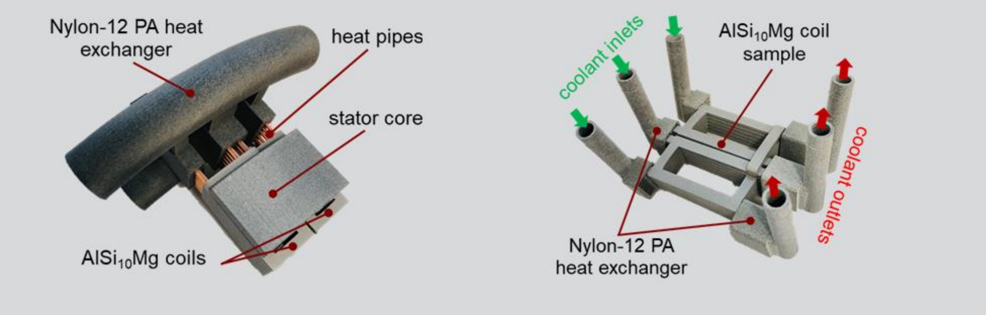
- In order to achieve the very demanding performance metrics, novel designs, novel, TMS, advanced manufacturing and materials all need to come together
- MU will build upon ongoing activities and experiences in aerospace applications, additive manufacturing and advanced electrical machines and drives
- FSU will build upon ongoing activities and experiences in advanced insulation systems with special focus on partial discharge
- NREL is the DOE's leading national lab in thermal management and has ongoing collaborations with MU
- Raytheon is a key player in aerospace and will lead the system integration and verification testing as well as help develop the technology to market plan

Motor + Power Electronics + TMS Innovation

- Novel additively manufactured hollow coils integrated with direct cooling.
- Modular power electronics tightly integrated with the electrical machine This leads to significant increase in specific power and elimination of long cables, filters, and connections which also improves system efficiency and reduces EMI issues.
- Wide Band Gap (WBG) devices (GaN) are used to enable high efficiency and higher switching frequency to directly drive individual coils with low inductance values and hence increase system specific power.
- Each power electronics module (which is a single-phase H-bridge) will be integrated and supply two coils belonging to the same phase representing the system building block . This modular approach will increase system fault-tolerance and reliability.
- Shared TMS between electric motor and drive
- Light-weight additively-manufactured heat exchangers







CHANGING WHAT'S POSSIBLE

Motor + Power Electronics + TMS Performance

- *A combination of analytical tools/models, FEA and optimization tools have been developed/used. This includes EM, thermal, mechanical, electrical fields and drive analysis.*
- *Some of the best practices we established for this project include: (1) **Co-design** is critical to develop an optimized system in such a multi-disciplinary project (2) **Double check** some of the critical analysis results by more than one person an in some cases more than one software (3**) Building and testing sub-components as early as possible** is critical for de-risking and modifying the design as needed (4) It is important to **work with more than one vendor** especially during the early stages of dealing with AM coils and heat pipes to define what is possible/feasible*
- *Tests performed so far: (1) AM coils characterization (2) Heat pipes characterization (3) Preliminary electrical and thermal tests on AM coils integrated with HPs (4) Preliminary testing of drive module (5) Insulation surface erosion testing*
- *Tests to be performed by end of phase 1: (1) Testing of multiple motorettes to confirm thermal performance with different HP configurations and cooling mediums (air and liquid) (2) Full testing of drive module (3)PD testing of some of the motorettes (if time/budget permits) (4)Vibration testing of some of the motorettes (if time/budget permits)*
- *What has been de-risked so far?: (1) AM coils properties and manufacturing limitations (2) HPs properties and manufacturing limitations (3) Impact of interface between the coils and the heat pipes (4) Design of composite rotor (partially) (5) Design of drive module (partially)*
- *What challenges remain? (1) Confirming the thermal performance of the motorettes (2) Confirming the performance of the drive module*
- ***What have we learned? Several lessons but key ones include: (1) AC losses is a key challenge and has to be carefully evaluated and mitigated (2) Tolerances and manufacturing limitations is another key challenge that needs to be carefully understood and accounted for (3) Relying on datasheets is not sufficient and characterization and verification testing is needed at various stages***

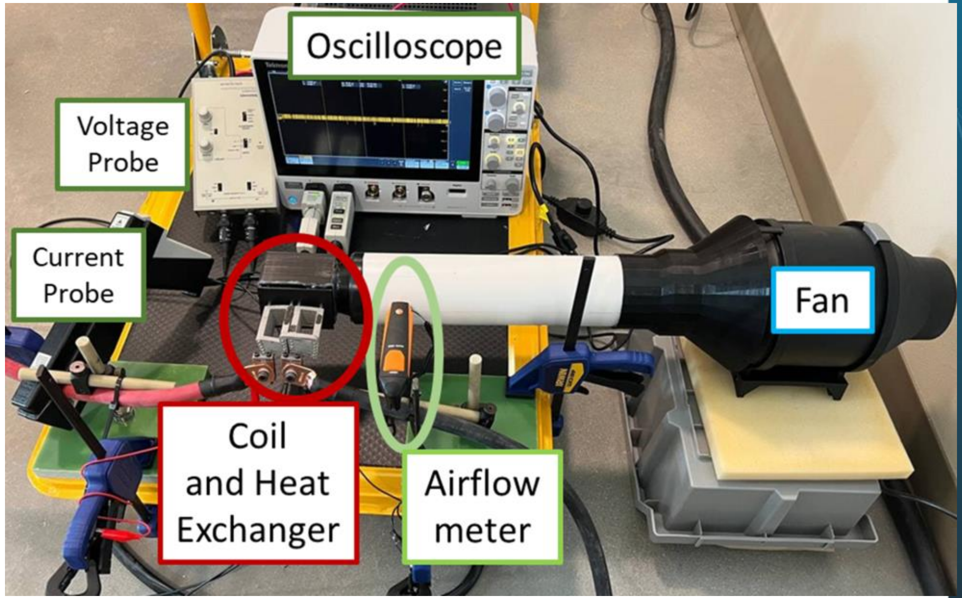
System Integration and de-risking testing

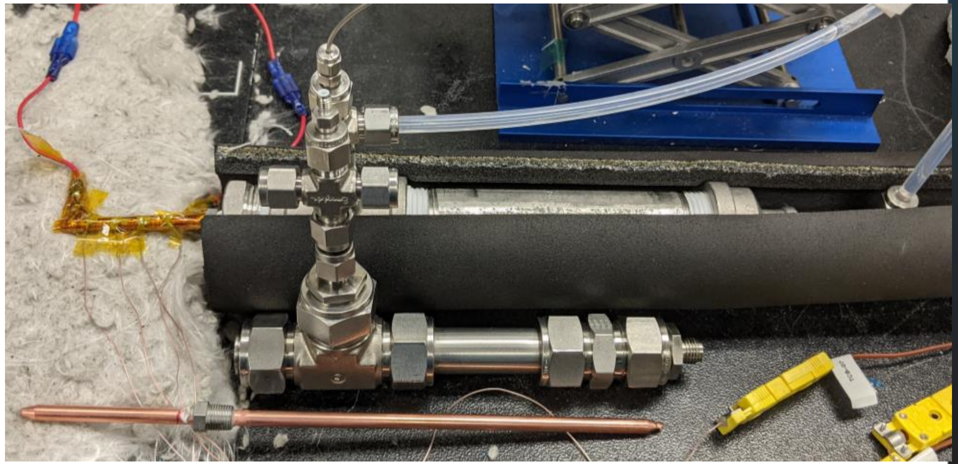
(1) Coil testing:

- *Tested a large number of coils of **different designs and vendors***
- *Testing to validate electrical conductivity and its thermal coefficient. In addition, independent testing performed at vendors.*
- *AC testing up to **140 Arms (0.52 pu) and 800 Hz**. Quantifying losses and confirming current carrying capability of the AM coils*
- *Quantifying the **impact of different interfaces** between coils and HPs*
- *Preliminary TMS testing based on both **air and liquid cooling***

(2) Heat pipe testing:

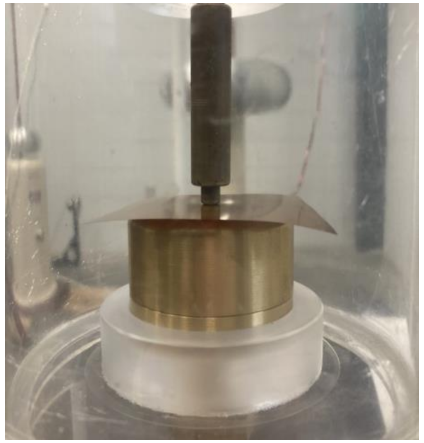
- *Tested a large number of heat pipes of **different sizes, lengths and vendors***
- *Both **round and flattened HPs** tested and Qmax quantified*
- *Impact of **condenser temperature** quantified*

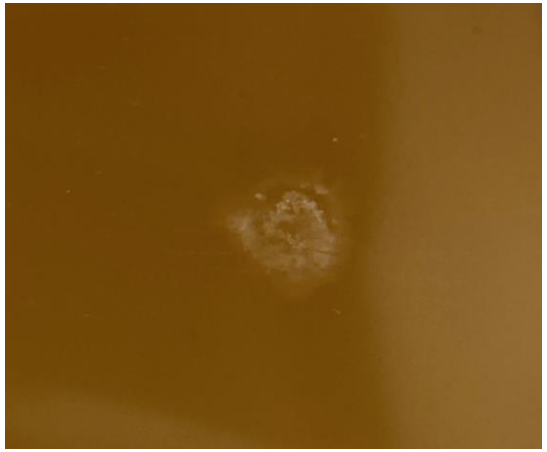




System Integration and de-risking testing

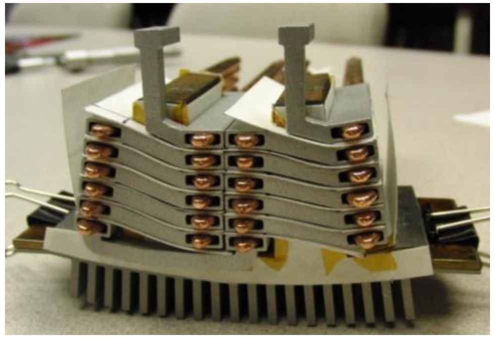
(3) Insulation surface erosion testing:





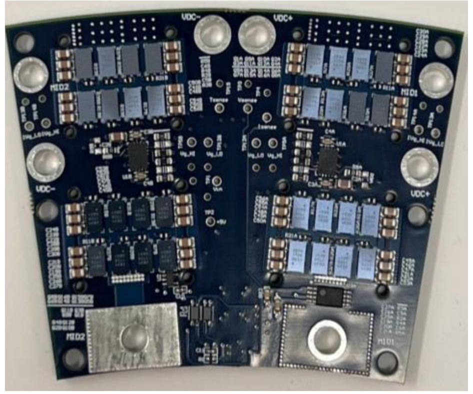
- *Test setup developed to measure insulation surface erosion under different voltage levels as a function of time*
- *Software developed to automate the testing process and data acquisition and analysis*

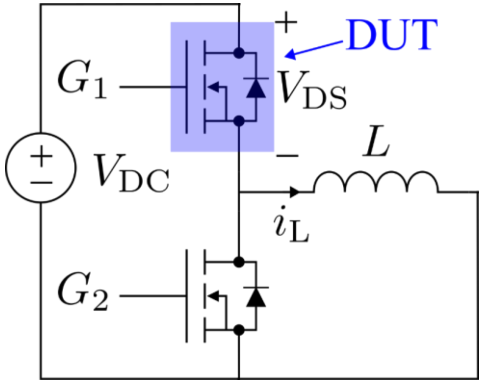
(4) Motorette testing:



- *First 1:1 motorette procured*
- *Thermal testing with both air and liquid planned*
- *PD and vibration testing planned*

(5) Drive testing:



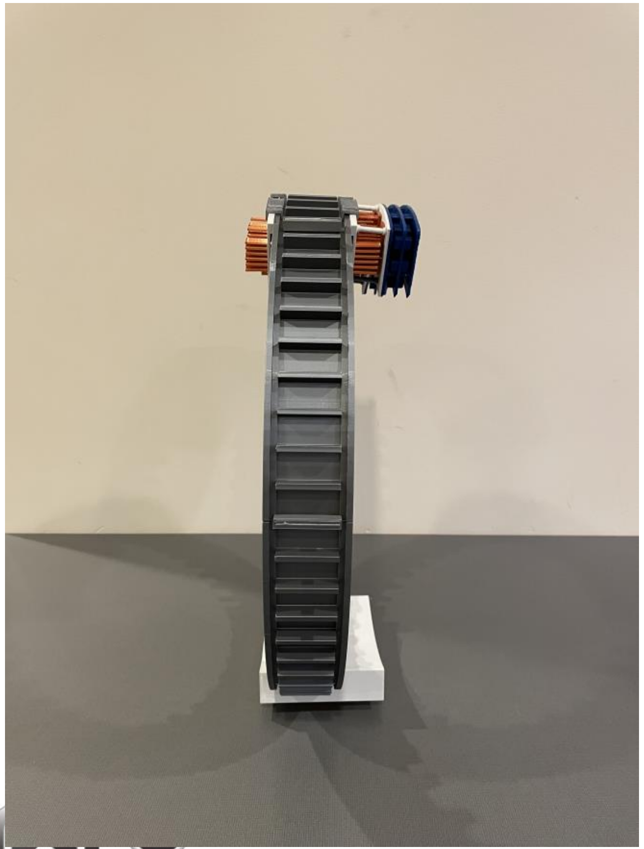


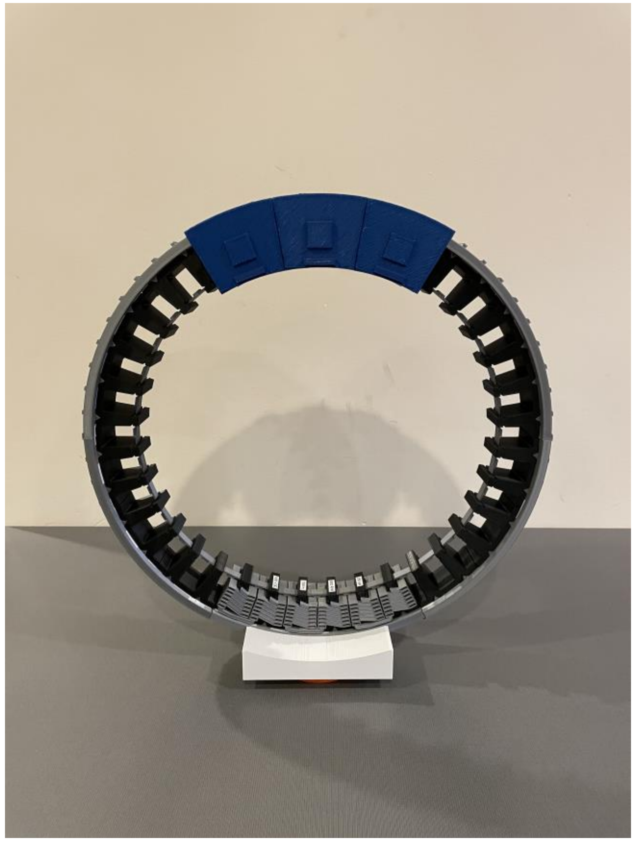
- *First drive module procured*
- *Initial double-pulse testing performed*
- *Full testing up to system rated conditions planned*

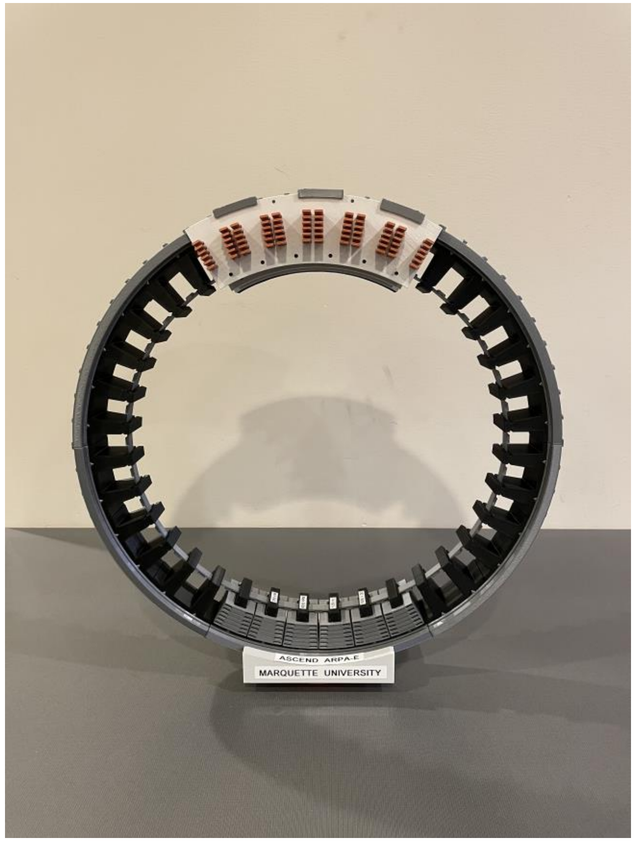
System Integration and de-risking testing

(6) Full-scale 3D system mockup/demo:

- *Help visualize the actual size of the system and how it is expected to look like*
- *Help confirm some tolerances and how things will fit together*

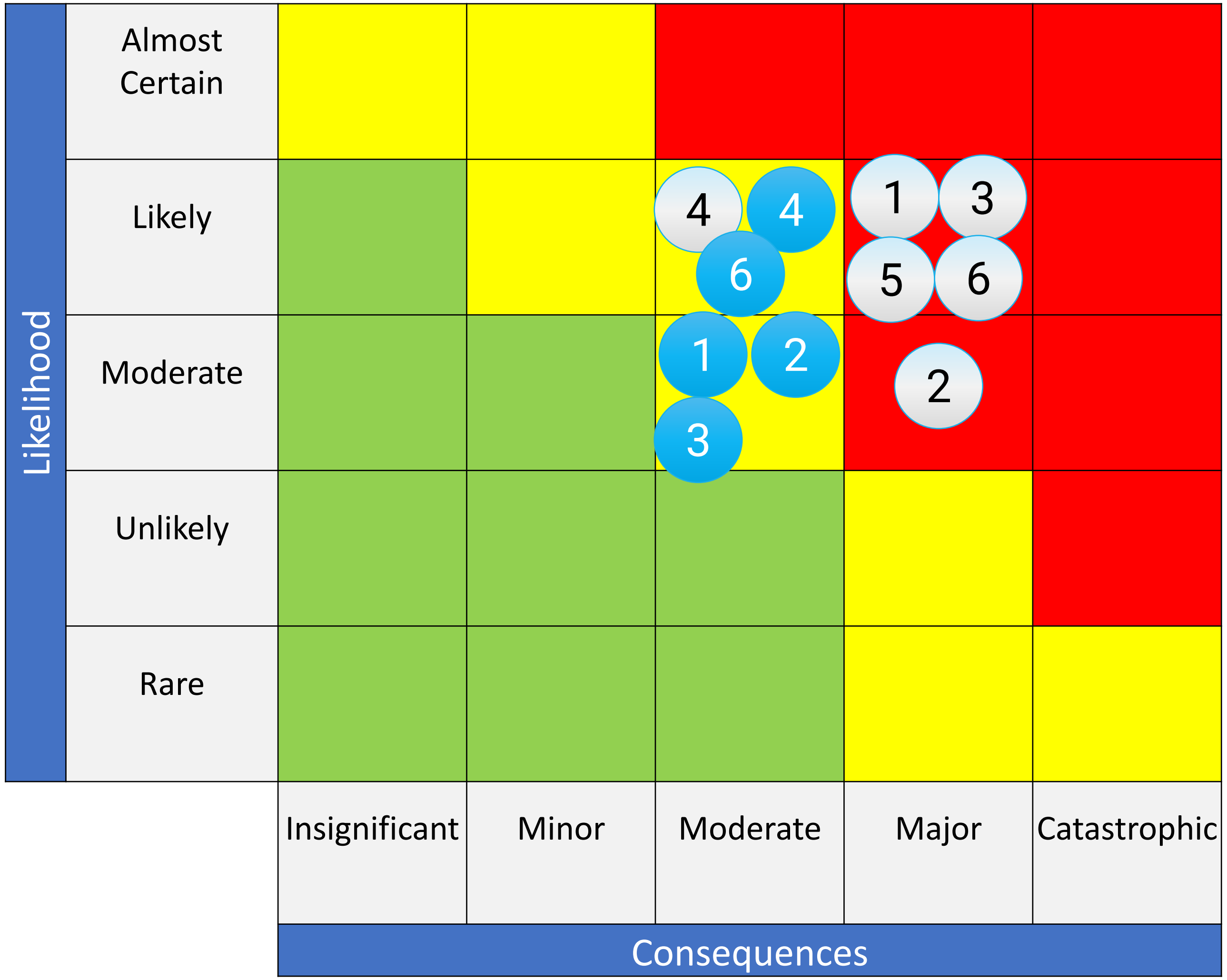






Risk Update

X Now X Start of project



Risk	#
Material property uncertainty	1
PD in insulation system	2
Effectiveness of TMS	3
Cascaded control and synchronization of power modules	4
Reliability and structural integrity of connections/interfaces between EM, TMS, and PE	5
Scalability and market adoption	6

Key risks all moved from "red" to "yellow". Some will be moved to "green" by end of phase I.

Technology-to-Market Approach and Update

- *The initial commercialization plan will be through licensing the technology. Other alternatives might be considered longer term*
- *Anticipated first market is urban mobility. Power ratings, speeds and mission profiles are relatively close to the current ASCEND specs.*
- ***We have been working with Ampaire to try to design a system based on their specifications to quantify the expected benefits***
- *Long terms markets will include large commercial aircrafts which will require scaling upof the technology to the MW-class and potentially higher speeds and system voltage.*
- *Based on the information we received from our partners, there seems to be some consensus regarding the anticipated first and longer-term markets. Certification is a significant process that will require some significant additional effort.*
- *Developed a cost model for the entire system and we keep updating it as we learn more. As expected, volume will have a significant impact on cost and potential partner(s)/vendor(s) are need to improve the estimates for mass production.*
- *~15 conference and journal publications. 1 patent application filed, and 4 more disclosures submitted.*

Needs and Potential Partnerships

- *Need to connected to more potential customers especially in the urban mobility space.*
- *Need to identify partners who can help with the certification process as well as the mass production of the system beyond the current award.*

CHANGING WHAT'S POSSIBLE

Looking Ahead – What is anticipated for an Eventual Phase II?

Please, list here what risks you plan to retire during the remainder of Phase I.

- Thermal verification testing of the motorettes to confirm effectiveness of the proposed approach
- PD and vibration testing of the motorettes (depending on time and budget)
- Verification testing of one drive module

Please, list here what risks you plan to retire during the eventual Phase II.

- Detailed system integration aspects will be addressed during phase II
- Individual full-scale component will be built, and testing will also take place during phase II
- Finally, a full-scale full-integrated system will be built, and tested to verify the predicted performance

Please, list here what you intend to do on the T2M side during the eventual Phase II.

- Continue to expand the IP portfolio to protect the developed technologies
- Continue to disseminate the accumulated knowledge via journal and conference publications
- Continue to refine the cost model especially based on the actual cost of building the full-scale components and system
- Connect with more potential customers and quantify the benefits of the proposed technologies based on their specifications
- *Try to have licensing and/or technology co-development agreements to commercialize the technology beyond the current grant*

Q & A

https://arpa-e.energy.gov